# Dual State Resonator Design for Plasma Ignition by Means of Microwave Energy

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## 1 Abstract

The paper describes the design of an microwave plasma ignition appliance to be used for gas discharge lamps. Field theoretical aspects are treated for the topology required to obtain ignition, also, the conductance of the plasma lamp is considered in the prior to- and after- ignition states. A solution is presented which offers coupling in of microwave energy for both conditions. The electromagnetic code WIPL has been used for the design steps.

## 2 Introduction

Modern analysis and disinfection processes are increasingly making use of irradiation of the treated substances. For instance, water can be disinfected by means of UV radiation. Conventional types of such UV installations incorporate electrode lamp radiators. However, the latter have only a limited life time and are not suited for applications requiring frequent on/off switching. At this point microwave energy can be advantageously used to circumvent the life time restrictions of the electrode lamps. A resonator, consisting of a quartz glass filled with gas, is excited by means of an RF generator. Resulting from the high field magnitudes at resonance, the plasma is ignited. Size and geometry of the quartz glass as well as the gas mixture are depending on the application. Figs.1 and 2 depict two different glass forms.

**Fig. 1a:** Test tube for fixture probe testing

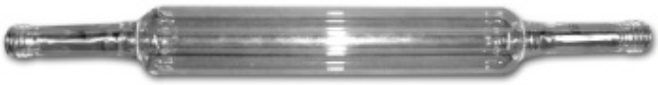

**Fig. 1b:** Test tube for continuous probe testing

A container for a stationary probe fixture (test tube) has been selected in Fig.1, while container 2 has been designed for continuous probe testing (flow testing).
Due to the given size of the glasses a practical frequency choice would be in the ISM range at 2.45 GHz. Microwave magnetrons constitute a common power source at this frequency range and offer outputs between 300 and 800W.

 

# 3 Theory

## 3.1 Field distribution in circular waveguides

Since the glasses are of tubular shape the usage of circular waveguides is a natural choice. For a given diameter and frequency the guided modes have to evaluated. In order to keep reactor size limited, lower order modes should be preferred. The glass container has to be uniformly supplied with microwave energy, for this reason all modes with any $\Phi$ - dependence can be excluded. Further considerations show that the modes of type $TM_{02}$ and $TE_{02}$ would leed to large reactor dimensions while $TE_{11}$ and $TM_{11}$ modes will not be symmetrical with respect to the z-axis [1]. Hence, $TM_{01}$ or $TE_{01}$ modes seem to be best suited for the application. The tube cutoff diameters can be evaluated by determining the zero-crossings of the Bessel functions: for the TM modes for the functions of n-th order and first kind and for the TE modes of the derivatives of the latter functions.

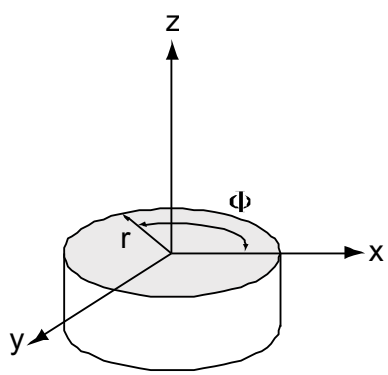


**Fig. 2:** Coordinate system

This will lead to values of $x_{01} = 2{,}405$ and $x'_{01} = 3{,}832$ for $TM_{01}$ and $TE_{01}$ modes, respectively. From those the cutoff-wavelengths will result

$$\lambda_{c(TM_{mn})} = \frac{\pi \cdot D}{x_{mn}} \text{ and } \lambda_{c(TE_{mn})} = \frac{\pi \cdot D}{x'_{mn}}, \tag{1}$$

alternatively, the minimum diameter can be determined for a fixed frequency.

## 3.2 Displacement current / Coaxial conductor current

Resulting from the field distribution in a circular guide two types of currents are present – displacement and wall currents. Once the plasma is ignited, the gas conductance changes, from a value of $\varepsilon_r$ close to 1 under normal conditions to a conductivity comparable to that of a metal conductor after ignition. For a glass tube located in a E-field maximum of the circular guide, this fact will have a serious impact – the field would be short circuited at this position - after plasma ignition - resulting in a deterioration of mode pattern and power matching. It is therefore crucial to incorporate two states into the design – a pre- and post-ignition topology. Fig.3 shows the field distribution of the $TM_{01}$ mode and the coaxial TEM mode.

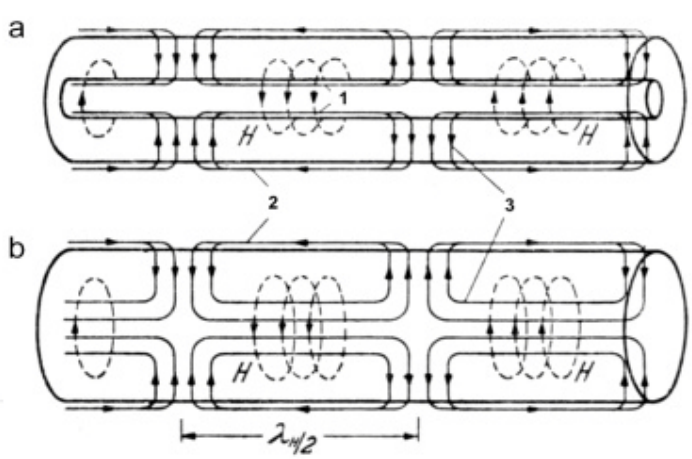


**Fig. 3:** Field distribution of the coaxial TEM mode and the $TM_{01}$ mode

 

Field distributions are similar, except for the fact, that the displacement current of the $TM_{01}$ wave is substituted by the coaxial line inner conductor current. Based thereupon, the idea behind the two state concept is now realized by placing the glass tube in such manner to function as inner conductor of a coaxial line, when the plasma becomes ignited. For highest power transfer the geometry of circular waveguide with glass tube and the coaxial line should have the same impedance in pre- and post- ignition states, respectively. The characteristic impedance of TM modes in the circular guide is written

$$Z_{TM} = Z_0 \cdot \frac{\lambda_0}{\lambda_g} \tag{2}$$

with

$$Z_0 = 120 \cdot \pi \cdot \Omega\,, \qquad \lambda_g = \frac{\lambda_0}{\sqrt{1-\left(\frac{\lambda_0}{\lambda_c}\right)^2}}\,, \qquad \lambda_c = 2 \cdot \pi \cdot \frac{a}{x_{mn}}\,, \qquad a = \frac{D}{2}\,,\ \lambda_0 = \frac{c}{f}\,,$$

where $D$ is metal tube inner diameter, $c$ the free space speed of light and $f$ the operating frequency (2.45 GHz). The air filled coaxial line has a characteristic impedance

$$Z_{Koax} = 60 \cdot \ln(\frac{D}{d}) \tag{3}$$

where $d$ denotes the outer diameter of glass tube. For a circular waveguide with $D = 92.7$ mm and glass having $d = 38$ mm the waveguide impedance is $54\,\Omega$ (glass filling excluded) the coax impedance $53{,}5\,\Omega$ both match well to the $50\,\Omega$ source impedance. However, it is expected that the field strength of the travelling wave originating from a 300 to 800W source will not be sufficient to ignite the gas in the glass cylinder.

### 3.3 Cylinder Resonances

A resonator can be formed by short circuiting both ends of a waveguide section. When the proper dimensions are chosen, constructive superposition of forward and backward travelling waves leads to a significant increase in field magnitude, expressed by the resonator quality factor. This property will be used to reach the ignition field strength.

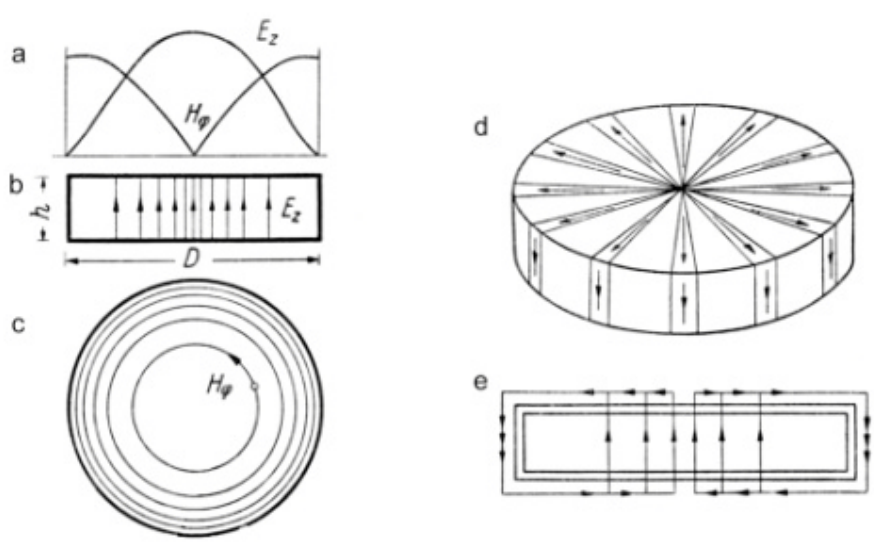


**Fig. 4:** Field distribution of the $TM_{010}$ mode [2]

 

Again, both states are to be considered, and the short positions should be carefully selected. For the case the $TM_{010}$ resonator mode is chosen prior to ignition, there will be only one mode in radial direction, see previous section eq. (2). This mode has field independence in direction along the cylinder axis. Fig. 4 shows the field distribution of the $TM_{010}$ mode.
Therefore, cylinder length becomes degree of freedom and can be used to accomplish the matching of the second state. This case is represented by a $50\,\Omega$ coaxial line short circuited at one end and fed according to Fig.5. It will become a coaxial resonator with capacitive coupling and an inner conductor consisting of plasma. The shape of the resonator feed and the dielectric properties of the quartz glass as well will have an impact on the design parameters. However their structures are too complex to enable an analytic solution, for this reason the EM calculation tool WIPL has been utilized.

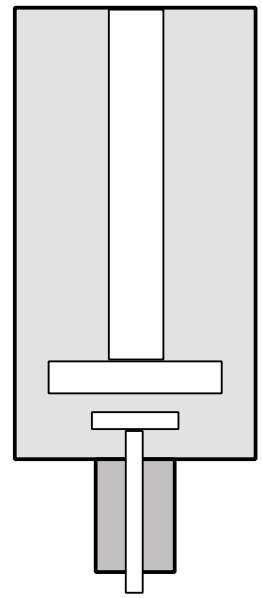

**Fig. 5:** Coaxial line short circuit

## 4 WIPL simulations of pre- and post - ignition states

Simulations of the pre-ignition state are based on a cavity resonator with a diameter gained by eq. (2) and under conditions of $50\,\Omega$ characteristic impedance. The geometry of the inner glass tube is gained by (3). Quartz glass is represented by a complex permittivity $\varepsilon_r = 3.7 - j0.77$ while the water content in the test tube is represented by the value $\varepsilon_r = 55 - j30$ .
As shown in the layout of Fig.6, the matching element on the magnetron feed has been analyzed and optimized for a configuration with $D = 92.7$ mm and $d = 38$ mm (inner diameter of circular guide and outer diameter of glass tube, respectively). For this modeling, the space between outer and inner quartz glass is filled with air. The matching to the generator impedance is a function of the magnetron feed tip geometry, the dielectric losses of water, quartz glass and the conductor losses of the outer conductor. Symmetry walls have been placed in $x$ and $y$ –planes in order to reduce the processing time. Once the feeding tip has been defined, it can be used to calculate the post-ignition state as depicted in Fig.6. Here, the former air section between the glass walls is now represented by a lossy conductor. Next, the length of the outer cylinder is optimized and finally, a test calculation is performed for pre- and post ignition states.
Figs. 7a and b show the E-field distribution for both states.

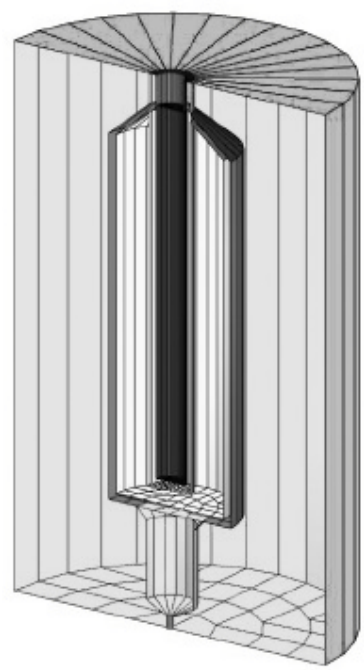

**Fig. 6:** Simulation Layout

 

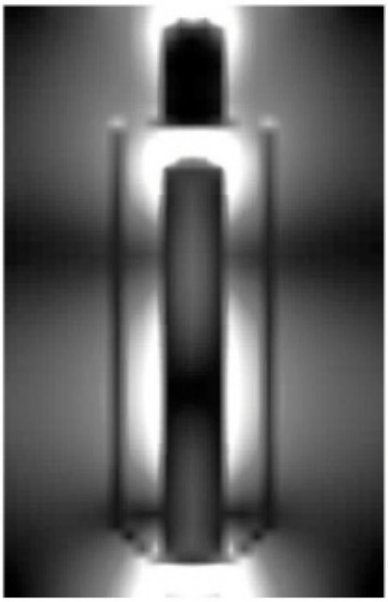

**Fig. 7a:** E-field distribution for pre ignition state

**Fig. 7b:** E-field distribution for post ignition state

One can clearly observe the local field maxima at the feed tip for both ignition states. The resonator is extending over 3/2 wavelengths. Due to the capacitive loading at the longitudinal resonator ends resulting from the glass to metal transition, the field maxima distance are shortened in this area.

## 5 Test Results / Comparison

A test structure has been developed and built of brass in order to verify the calculation results. The quartz glass tube and its gas mixture have been manufactured by UMEX GmbH of Dresden, Germany.
Measurements of the pre-ignition state have been performed with a vector network analyzer Wiltron / Anritsu 37347C. In this case the feed tip has been extended out of the resonator ending in a N-type coaxial connector.
Inherently, the post-ignition state can only be evaluated under power conditions. For this purpose a test system made by Richardson has been used, which offers generator power settings between 300W and 3000W and measurement of forward and backward reflected power. For the test, a magnetron equivalent has been developed, which emulates the feed tip of the actual magnetron, however is supplied by a WR-340 waveguide by the test system. A 50W return power has been measured for a forward of 400W, equivalent to a return loss of –9 dB. Figs. 8 and 9 show the calculated (WIPL) and measured matching properties.

 

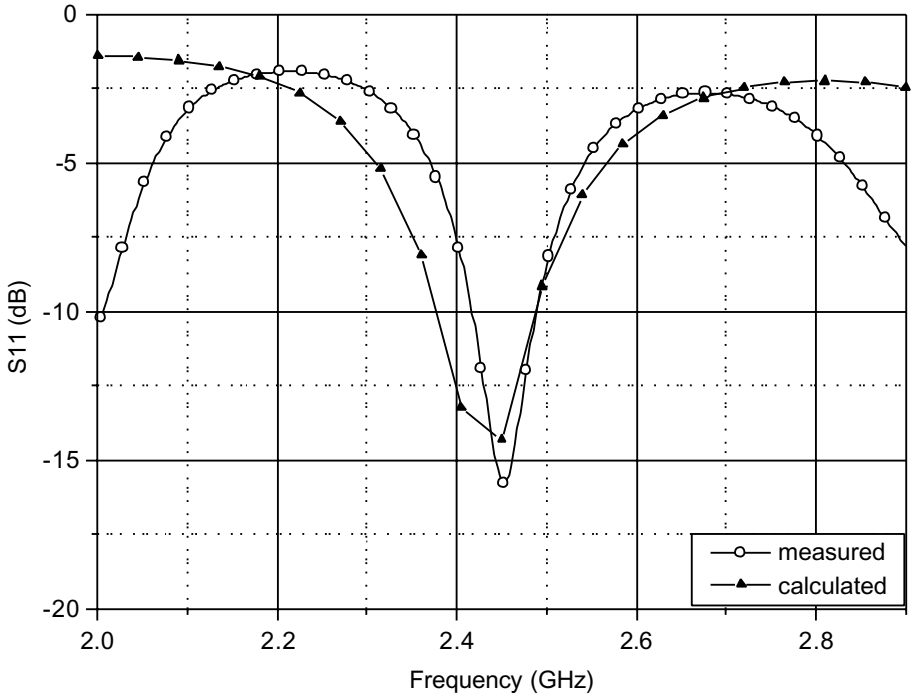


**Fig. 8:** Calculated and measured matching for pre ignition state

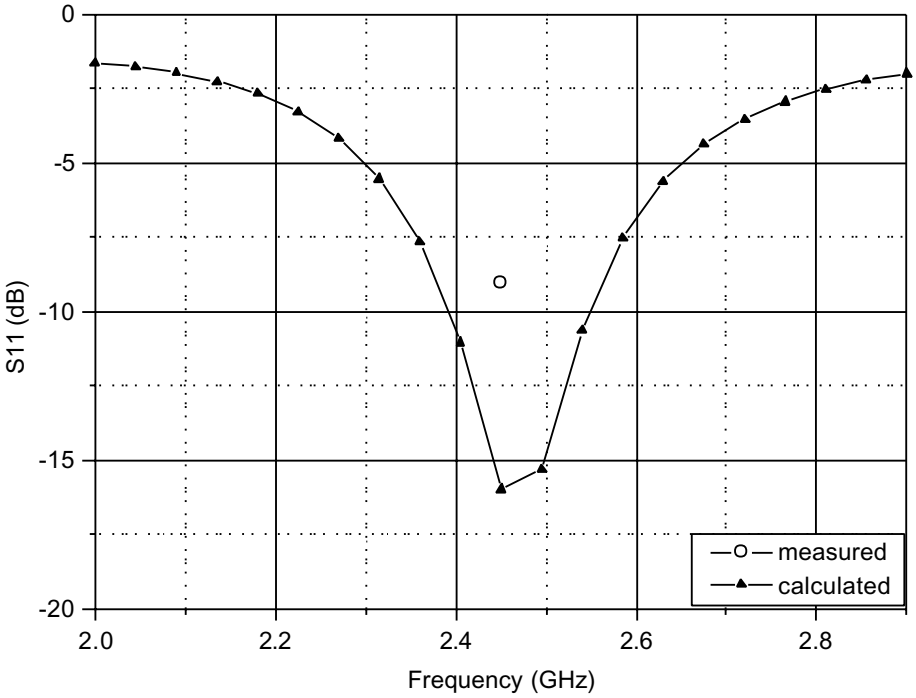


**Fig. 9:** Calculated and measured matching for post- ignition state

 

## 6 Conclusions

The paper has described the theoretical steps for the development of a microwave excitation system for plasma lamp. The design target has been to achieve a high degree of microwave power transfer for two different states – prior to and after the ignition of plasma (pre- and post-ignition states). A dual state resonator configuration has been designed. The field calculations have been performed with the help of the EM simulator WIPL. With the determined physical parameters a test device has been manufactured and measured in both ignition states. Good agreement is found between measured and predicted data for the pre-ignition state, while for the post-ignition state only one measurement point has been available at this time. Further test for this state, as well as a characterization of the plasma properties will constitute further steps in this work. Fig.10 depicts the test device with a 300W generator.

**Fig. 10:** Test device with a 300W generator

## 7 Literature

[1] Reich, Ordung, Kraus, Skalnik, „Microwave Theory and Techniques", Van Nostrand Company, 1953, S.278

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[3] B.M.Kolundzija, J.S.Ognjanovic, T.K.Sarkar, WIPL-D:„Electromagnetic modeling of composit metallic and dielectric structures", Software and User's Manual, Boston: Artech House, 2000

## 8 Acknowledgement

The author would like to express his thanks to Prof. B.M. Kolundzija, University of Belgrade, for his generous support and the numerous useful comments regarding the usage of the WIPL-D code.

 